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# **Palaeohydrological Corridors for Hominin Dispersals in the Middle East ~250-70,000 years ago.**

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## **Abstract**

The timing and extent of palaeoenvironmental connections between northeast Africa, the Levant and the Arabian Peninsula during the Middle and Late Pleistocene are critical to debates surrounding dispersals of hominins, including movements of *Homo sapiens* out of Africa. Although there is evidence that synchronous episodes of climatic amelioration during the late Middle and Late Pleistocene may have allowed connections to form between northern Africa and western Asia, a number of palaeoclimate models indicate the continued existence of an arid barrier between northern Arabia and the Levant. Here we evaluate the palaeoenvironmental setting for hominin dispersals between, and within, northeast Africa and southwest Asia during Marine Isotope Stages (MIS) 7–5 using reconstructions of surface freshwater availability as an environmental proxy. We use remotely sensed data to map palaeohydrological features (lakes, wetlands and rivers) across the presently hyper-arid areas of northern Arabia and surrounding regions, integrating these results with palaeoclimate models, palaeoenvironmental proxy data and absolute dating to determine when these features were active. Our analyses suggest limited potential for dispersals during MIS 7 and 6, but indicate the formation of a palaeohydrological corridor (the ‘Tabuk Corridor’) between the Levant and the Arabian interior during the MIS 6-5e glacial–interglacial transition and during MIS 5e. A recurrence of this corridor, following a slightly different route, also occurred during MIS 5a. These palaeohydrological and terrestrial data can be used to establish when proposed routes for hominin dispersals became viable. Furthermore, the distribution of Arabian archaeological sites with affinities to Levantine assemblages, some of which are associated with *Homo sapiens* fossils, and the relative density of Middle Palaeolithic assemblages within the Tabuk Corridor, are consistent with it being utilised for dispersals at various times.

## 1. INTRODUCTION

Pleistocene out of Africa hominin dispersals are key events in human evolution. When evaluating the routes such dispersals may have followed, it is clear that the Levant and northern Arabia represent critical regions connecting the Sinai Peninsula, the only terrestrial route out of Africa, to Eurasia during the Middle and Late Pleistocene (Petraglia and Alsharekh, 2003; Derricourt, 2005; Lambeck et al., 2011). The climates and environments that prevailed in these regions during the late Middle and Late Pleistocene would therefore have been a primary control on the timing and extent of hominin dispersals, including those of *Homo sapiens*, via this continental route.

The terrestrial route via the Sinai is of special interest in human evolutionary studies, as the earliest documented fossils of *Homo sapiens* known outside Africa were found in the Levant, and date to ~130–90,000 years ago (ka) (Valladas et al., 1988; Grün et al., 2005), suggesting that an important dispersal event occurred during (or prior to) Marine Isotope Stage (MIS) 5. However, interpretations vary on whether this was a locally limited ‘failed dispersal’ (Mellars, 2006a, 2006b; Oppenheimer, 2009, 2012; Mellars et al., 2013) or part of a wider expansion that extended into Arabia and southwest Asia (e.g. Petraglia et al., 2010; Armitage et al., 2011; Rose et al., 2011; Boivin et al., 2013; Groucutt et al., 2015a,b). Subsequent relatively unambiguous evidence for the presence of *Homo sapiens* outside Africa is not known until MIS 3 in Southeast Asia and Australia. For example, fossils from Tam Pa Ling cave, Laos, have been dated to ~63–43 ka (Demeter et al., 2012, 2015), and those from Lake Mungo, Australia, to ~50–45 ka (Bowler et al., 2003), although emerging East Asian fossil evidence is consistent with a much earlier arrival of *Homo sapiens* (Liu et al., 2015). However, species attributions based on lithic assemblages from intervening locations and time periods remain controversial, and estimated dates based on genetic data for key evolutionary events such as dispersals are currently strikingly variable (compare Scally and Durbin, 2012; Mellars et al., 2013; Groucutt et al., 2015a). There is therefore considerable ambiguity in the potential extent and chronology of hominin dispersal events in the Middle East during the late Middle Pleistocene and Late Pleistocene, and the species involved.

Here we consider the potential for hominin dispersals out of Africa via a northern (trans-Sinai) route to the Levant and northern Arabia (Figure 1) during the late Middle to Late Pleistocene (MIS 7–4), a time period spanning the MIS 5e (Last Interglacial) interval associated with widespread environmental amelioration. These regions occupy a critical geographical position for evaluating the spatial extent of dispersals via the Sinai route, although the archaeological and palaeoenvironmental records from Arabia are currently less well understood than those of the Levant and North Africa. Here, we focus on data from the Nefud Desert, northern Saudi Arabia (Figures 1 and 2), where dated Middle Palaeolithic stone tool assemblages indicate the presence of hominin populations during MIS 7, 5c and 5a (cf. Petraglia et al., 2011, 2012). Moreover, numerous records of undated typo-technologically Middle Palaeolithic assemblages from across northern Arabia indicate that these were far from isolated occurrences (cf. Groucutt and Petraglia, 2012; Figure 1). This emerging body of archaeological evidence raises important questions pertaining to regional connections, and the routes by which these hominin populations penetrated the Arabian Peninsula.

Most of the region is hyper-arid at present (Figure 2), however, as will be discussed here, episodic climatic amelioration occurred during the Pleistocene. During these events the distribution of surface freshwater would be a significant control upon the penetration of this area of the mid-latitude desert belt (*sensu* Finlayson, 2013, 2014; Groucutt and Blinkhorn, 2013), as humans require abundant freshwater on a virtually daily basis, particularly in deserts, where high temperatures compound heat stress and water loss. Furthermore, several lines of evidence are indicative of a persistent arid barrier

across northern Arabia, even during amelioration episodes (N. Arabian Desert Barrier, Figure 2). We therefore combine catchment-level palaeohydrological analyses and distribution data for Middle Palaeolithic archaeological sites, to examine relationships between reconstructed palaeohydrological corridors and evidence for hominin dispersals into northern Arabian Desert. The resulting palaeohydrological mapping provides a basis for testing hypotheses relating to potential migration routes exploited by humans and other animals in terms of freshwater availability.

### Study area.

The study area encompasses northeast Egypt, the Sinai Peninsula, the Levant, northern Arabia and the Lower Euphrates (Figure 1), which constitute the critical region for modelling terrestrial routes out of Africa. The term ‘northern Arabia’ is here defined as the arid region east of the Sinai Peninsula, including parts of southeast Jordan, southern Iraq, and northern Saudi Arabia (Figure 2). It has been suggested that dispersals could have occurred across the Jordanian desert plateau during Pleistocene wet phases, for which two routes have been proposed (Figure 1). The first, the ‘Azraq Corridor’, connects the Levant to Arabia via northern Jordan and along the Wadi Sirhan depression (Cordova et al., 2013; Ames et al., 2014; Ames and Cordova 2015). The second, is a southern route from the Negev to the Nefud (hereafter the ‘Tabuk Corridor’), inferred from hypothesised palaeoclimatic connections between these areas (Vaks et al., 2007; Waldmann et al., 2010; Frumkin et al., 2011; Parton et al., 2015b). It is also possible that hominin populations circumvented much of the northern Arabian desert via an extension of the ‘Levantine Corridor’ (Bar-Yosef, 1987) reaching the Lower Euphrates (Por, 2004) (hereafter the ‘Euphrates Corridor’) from where subsequent dispersal into northern Saudi Arabia might have occurred from the northeast (Figure 1). The Levant is a common factor in all of these hypothesised dispersal routes, and may have been episodically connected to Africa via the Sinai (Figure 1), potentially providing the source populations for dispersals into Arabia (Derricourt, 2005). Southern dispersal routes across the Red Sea via the Bab al Mandab (e.g. Derricourt, 2005; Lambeck et al., 2011; Oppenheimer, 2012b; Armitage et al., 2015) are not considered here as they lie beyond the study area; however, the potential for such trans-Red Sea dispersals cannot be ruled out. Potential routes *exclusively* utilizing exposed coastal shelves (Stringer, 2000) are also not considered, as they cannot be evaluated using the methods employed here (though see Groucutt et al., 2015a, for discussion), although terrestrial components of any routes along the coastal peripheries, or striking into the interior from these areas, are.

## 2. MATERIALS AND METHODS

Palaeohydrological features (drainage courses, palaeolakes and marshes, and their associated catchment areas) were mapped across the study area and published palaeoenvironmental data from dated sequences were used to determine when these catchments received substantial precipitation within the period spanning MIS 7-5a. A spatial database of Middle Palaeolithic archaeological sites was compiled, and integrated with the palaeoenvironmental and catchment humidity data, in order to identify evidence for hominin dispersals via humid catchments at specific times.

### 2.1 Palaeohydrological mapping

Palaeohydrology was mapped using remote sensing and GIS (Geographic Information System) techniques, applying the methodology developed by Breeze et al. (2015) to identify relict drainage systems, lakes and wetlands across c.1 million km<sup>2</sup> of northern Arabia. Flow accumulation data were calculated from HydroSHEDS 3AS data (Lehner et al., 2008) to map major surface and shallow sub-surface palaeodrainage at ~90m resolution, classified by quantification of contributing upstream areas.

All drainage systems shown in our paper have a minimum of 1000 km<sup>2</sup> of upstream contributing area, a conservative threshold for delineating major fluvial systems. Outside the desert survey area, the modern courses of rivers such as the Nile, Orontes and Euphrates are shown, unless major course changes during the late Middle–Late Pleistocene can be mapped. Palaeolake and marsh deposits in endorheic basins >1km<sup>2</sup> in area were mapped, and potential maximum former lake/marsh extents modelled, following the methods outlined in Breeze et al. (2015), which were applied to SRTM data (Jarvis et al., 2008) and 52 Landsat TM satellite images. This allowed rapid, semi-automated detection and mapping of lacustrine and marsh deposits, although discrimination between these environments was not possible as both have similar spectral signatures. This is a strength of the method, since individual palaeohydrological features in arid regions fluctuate repeatedly over time along a palaeohydrological spectrum, from perennial lakes, through wetlands and marshes, to seasonal playa and ephemeral saline lakes, in response to changing geomorphological, seasonal and palaeoenvironmental factors (Bowler, 1986). A variety of these conditions may therefore provide surface freshwater and result in deposits later preserved in the geological record; the mapping method is therefore designed to recognise this range of potential freshwater sources.

Several large topographic depressions in the northern Arabian desert region witnessed recurrent lake formation during successive humid climatic phases (Macumber, 2008; Petit-Maire et al., 2010; Cordova et al., 2013; Petraglia et al., 2012; Hilbert et al., 2014; Mischke et al., 2015). Here we therefore reconstruct these lakes during each wet phase, although for basins where securely dated sequences are not yet available the detected deposits could represent a single lake phase or multiple lake phases. Potential maximum former extents of wetland/lake features are based on the altitude attained by the highest surviving deposits in each basin. For any given time period the reconstructed lake features provide only an indication of the location and potential size of hydrological features and cannot be used to infer absolute contemporary extents. Elsewhere, such as in the Dead Sea basin, lakes exhibit clear shoreline data from which maximum extents can be calculated with more certainty (e.g. Waldmann et al., 2009). Here, the maximum extent of Palaeolake Samra (Waldmann et al., 2009) is displayed, being broadly representative of the maximum extent of this lake during interglacial phases. It should be noted however that during MIS 6, its precursor, Lake Amora, exceeded this size (Torfstein et al., 2009).

As discussed further below, catchment reconstruction is important both as a means for spatially distributing environmental proxy evidence for humidity and for determining potential opportunities for hominins to move into new areas. During periods when adjacent catchments were both wet, proximity of drainage systems or lakes close to the catchment divide may have allowed humans and animals to cross over the catchment divide while remaining close to water, facilitating expansion into new areas (cf. Drake et al., 2011). Catchments were derived using HydroBASINS (Lehner and Grill, 2013), which delineates nested watersheds based on Pfafstetter ordering. Displayed catchments were derived from the Pfafstetter level 4 data, which divided the area into principal catchment regions (e.g. the Dead Sea and Sirhan Basins, the Euphrates watershed). Where further subdivision of catchments was required (i.e. if spatial distributions of proxy data or the potential extents of palaeoprecipitation sources indicated that only select sub-catchments of larger basins may have been wet), level 5 catchments are displayed as sub-basins of the large catchments. The mapped catchments were then combined with environmental proxy data to explore when their palaeohydrology may have been active.

These hydrological maps unavoidably use current topographic data as their basis (see Breeze et al., 2015), making it necessary to evaluate application of these data to the Pleistocene (discussed further in the supporting information- SI1). As regards northwest Arabia, incision of the major drainage net pre-dates the periods of interest, during and subsequent to which, aggradation and flow reactivation along

the course of prior major channels appear dominant (Hötzl and Maurin, 1978; Hötzl et al., 1978a, 1978b, 1978c, 1978d; Anton, 1984; Edgell, 2006; Wilson et al., 2014). Mapped rivers follow major valleys, with no significant re-organisation of these drainage divides and flow directions through uplift (Wilson et al., 2014), faulting, or volcanic over-printing since the late Middle Pleistocene (SI1). River locations therefore appear not to have changed dramatically since the periods of interest. In dune fields, topography may have altered substantially, however throughout the later Pleistocene the areal extent of at least the southern and western Nefud (the only contemporary erg) appears similar to present, with all local lakes being interdunal (SI1). Positions and morphology of dunes and interdune basins may have changed within this area; nonetheless, *locations* of mapped palaeolakes are accurate, being based on detected deposits. As both the location and interdunal character of the Pleistocene lakes are consistent with their present topographic setting, we display modern dune topography (and lake extents based upon it) as a broad analogue for contemporary conditions when the mapped lakes formed. It is clear that dated interdunal lakes were not isolated features (Rosenberg et al., 2013; Scerri et al., 2015), hence, for periods with dated lakes we display all lakes mapped locally as an appropriate representation of the contemporary local situation. Given the likelihood of further deposits being buried beneath dunes, lake mapping in this area should be considered a minimum estimate.

Finally, several factors could influence surface flow within mapped catchments and downstream propagation of drainage, particularly the spatio-temporally complex local interplay of precipitation with infiltration and soil composition, vegetation cover and evaporation. Unfortunately, as regards Pleistocene northern Arabia, data regarding these variables remain extremely spartan and uncertain, inhibiting reliable evaluation of their distribution and characteristics, let alone their collective dynamic influence upon local hydrology. While the hydrological datasets are therefore not without limitations, we highlight that to date they provide the most detailed and spatially comprehensive models of the distribution of former surface water resources across northern Arabia. We therefore utilise these data to propose new spatially explicit hypotheses for evaluation in light of present data, and testing through future survey.

## 2.2 Palaeoenvironmental proxies

To determine the timing and intensity of hydrological activity within reconstructed catchments, a database of dated terrestrial palaeoenvironmental records was compiled for the study area. Radiometric ages associated with proxies indicating increased precipitation (such as fluvial, palustrine, lacustrine and speleothem deposits) and dated to between MIS 7 and MIS 5a were assembled (319 dates, Tables 1-4), along with age models derived from Levantine lake cores (Gasse et al., 2015; Torfstein et al., 2015) and fluvial terrace correlations (Bridgland et al., 2012). Data from northeast Africa were included, in the form of evidence for periods of substantially enhanced Nile flow (indicated by sapropels; Williams et al., 2015), and proxies indicating terrestrial humidity in the lower Nile and adjacent catchments. The spatial distribution of the dated local precipitation proxies is shown on Figure 3, classified by MIS of the date mean (using the LR04 chronology of Lisiecki and Raymo, 2005). This highlights the sparsity of dated humid proxies from northern Arabia, limiting our ability to define corridors in the area. Direct dates for humidity are also absent from the central and western Sinai Peninsula and lower Euphrates/Iraq/Syrian desert, reflecting historical difficulties in undertaking fieldwork in these regions. In the case of the Lower Euphrates, extensive Holocene alluviation has obscured both archaeological and palaeoenvironmental records pertaining to the late Middle and Late Pleistocene.

Additional data pertaining to conditions during the penultimate Interglacial/Glacial transition (c.130 ka) were obtained from rainfall estimates derived from the CCSM climate model (Jennings et al., 2015, and Figures 2, 9 and 13). These estimates are useful for regions where sedimentary archives are poorly-known or absent, as noted above, although it has been noted that many climate models underestimate rainfall quantities in the Sahara (Perez-Sanz et al., 2014) and potentially also in Arabia (Jennings et al., 2015). Sea-level evidence for key periods was utilised to illustrate exposed former coastal shelves, with Pleistocene sea-level estimates for the Red Sea (Lambeck et al., 2011) used to threshold ETOPO1 combined elevation and bathymetric data (Amante and Eakins, 2009). We acknowledge that this application of these Red Sea data to a wider region is a very limited ‘broad brush’ approach in the absence of further detailed isostatic and crustal modelling work in the region (*sensu* Lambeck et al., 2011).

### 2.3 Regional Middle Palaeolithic archaeological data

A database of techno-typologically Middle Palaeolithic sites (both surface occurrences and dated, stratified assemblages) was assembled for northeast Africa, the Levant, northern Arabia, Syria and Iraq based on published data (Groucutt and Petraglia, 2012; Groucutt et al., 2015a, 2015b, 2015c; Hilbert et al., 2015; Shea, 2003, 2013 and references therein) and new fieldwork (Figure 1). Spatial positions for the sites were plotted using published coordinates or geo-referencing of published maps.

### 2.4 Data integration

These datasets were incorporated into a spatial database, allowing GIS overlay analysis to link dated humidity to catchments and, by extension, to the other palaeohydrological features within these. This allowed maps of humid catchments and activated hydrology to be produced (section 4) for different marine isotope stages (cf. Drake et al., 2011). These maps were overlain with archaeological data and examined for significant spatial patterns (section 5). We evaluated technological similarities between lithic assemblages based on published data, particularly in terms of core reduction methods, and where we were able to directly analyse the material by following the methodology outlined by Tostevin (2012) and Scerri (2013; Scerri et al, 2014a). While detailed comparative studies need to be conducted to further refine our understanding of regional stone tool technology, our aim here is to integrate broad special-temporal patterning in lithic variability with regional environmental fluctuation. Though the drivers of lithic variability remain much debated, the presence of lithic artefacts provides a robust signal for the presence of humans in particular spatial and temporal contexts.

As Pleistocene shifts in the receipt of moisture from the major climate systems were dominantly latitudinal (i.e. north/south movements relative to their present position), catchments immediately east or west of documented humidity (within the known extents of the climate systems) were also inferred to be humid and marked accordingly, where paleoclimate evidence supported this conclusion (see discussion). Case-by-case discussions of catchment level evidence are given in the Supporting Information (SI). Data suggest that the Nile, Euphrates and Orontes likely flowed throughout our periods of interest. For those periods where this is corroborated by dated proxies, their catchments are displayed as humid. For those periods when it is not, a buffer (30 km) is applied to the river to visually represent that while it originates in a humid area (i.e. is allogenic), there is no evidence that the area surrounding it in the arid zones was ameliorated, beyond the immediate vicinity of the channel.

The data were used to determine if, where, and when, synchronously wet catchments could have provided corridors for regional dispersal. Where potential corridors were identified, GIS kernel density

mapping of the humid proxy data was used to investigate their spatio-temporal character. Time-slices of 3 ka width were defined spanning the periods of interest, and for each a GIS shapefile was produced that contained geolocated points for every proxy date with a  $\pm 1$  sigma ( $\sigma$ ) error range overlapping this 3 ka period. Maps were then produced for each time-slice using the Kernel density function of ArcGIS 10.2 (derived from Silverman, 1986). These maps display the spatial density of point locations as spheres of increasing size and colour intensity, based upon the number of points falling within a default search radius around each point (determined by an algorithm accounting for sparse datasets). This visually highlights spatial clusters, and therefore comparison of maps for different time-slices illustrates spatial and temporal clustering of precipitation proxies (considering  $1\sigma$  confidence intervals), allowing examination of when (based upon the greatest overlap of probability ranges for dates) humidity along the corridor was most likely to have occurred and how this changed over time.

The method reported here requires that there is enough proxy data to represent the past hydrology of the region. If information is absent, due to either survey or preservation bias (see 2.2. above), formerly connected corridors that may have existed cannot be demonstrated. The adage that ‘absence of evidence is not evidence of absence’ applies; these analyses can demonstrate where evidence supports the presence of active hydrology, but do not confirm its absence elsewhere.

The advantage of the catchment-level method is that it allows available proxy evidence to be interpolated to its largest sensible hydrological unit (the local catchment), while also mapping at high resolution the features within this that are meaningful at the human scale (drainage, lakes and marshes). This facilitates determination of whether major hydrology in adjacent wet catchments could have been close enough to facilitate dispersals between catchments. To do this non-Euclidean GIS path distance analyses (performed in ArcGIS 10.2, using SRTM data) were used to examine distances between freshwater sources.

### 3. RESULTS: REGIONAL PALAEOHYDROLOGICAL RECONSTRUCTIONS

Here we discuss the results of the palaeohydrological mapping, before integrating these data with the regional palaeoenvironmental record for specific periods.

#### 3.1 Regional palaeohydrology

The results of the palaeohydrological mapping of the region are shown in Figure 4. These data for arid northern Arabia define 56,377 km of large drainage courses, together with ~2809 palaeolake locations (with combined maximum former extents covering an area of up to 18,912 km<sup>2</sup>), collectively providing the most spatially comprehensive and highest-resolution (c.90m) map of northern Arabian palaeohydrology to date. The dataset indicates that several groups of catchments could potentially provide connections between the Levant and Nefud regions. The most direct of these cross the Jordanian desert via two routes shown in Figure 1. The palaeohydrology of these northern (Azraq) and southern (Tabuk) corridors, and the chronology of the humid proxies associated with these, are displayed in Figure 5, and discussed in the subsequent sections.

##### 3.1.1 Azraq Corridor

The Azraq Corridor has the potential to have been an important route for dispersals (Cordova et al., 2013; Ames et al., 2014; Ames and Cordova, 2015), stretching from the Dead Sea via Azraq and a series of sub-catchments along the Wadi Sirhan depression to the Nefud (Figure 5c). Our data supports the



potential for a palaeohydrological connection along this route, providing that at least four adjacent sub-catchments within the Sirhan depression were simultaneously humid (Figure 5c and SI1). The large number of humid sub-catchments required to form this corridor is due to the primary drainage in these basins being perpendicular to the axis of the larger Sirhan depression, rather than parallel with it, resulting in a chain of separated lake/wetlands that only if synchronously active could have provided a connected route. We speculate that in the central portion of the Sirhan basin lake formation could have potentially been facilitated by receipt of moisture from the south through a cascade process via Wadi Fajr (Figure 5c). If upper Wadi Fajr activated, the shallow, small lake, which it feeds (perched on the catchment divide with the Sirhan depression) would have filled and overtopped, feeding into the Qa Hazawa palaeolake in a central sub-basin of the Sirhan depression. This could also have provided an additional connection to the Nefud (see SI1 for further detail). Figure 5c highlights however that at present no dated palaeoenvironmental sites exist in the Fajr catchment to confirm such an occurrence, or along Wadi Sirhan east of the Azraq sub-catchment (location 4, Figure 5c), where available dates and proposed lake activity phases have large uncertainties (Figure 5a).

### 3.1.2 Tabuk Corridor

The second possibility is a route from the Dead Sea to the Nefud via the Mudawarra/Tabuk depression (Figures 5c and 5b). Recognising synchronous MIS 5e humidity in the Negev, Mudawarra and the Nefud, several studies (e.g. Vaks et al., 2007; Waldmann et al., 2010; Frumkin et al., 2011) have suggested contiguous climatic amelioration across this region, and Parton et al. (2015b), hypothesised a potential connection might have existed via Mudawarra. However, climatic overlap between the westerlies and monsoons remains disputed and the moisture source for Mudawarra ambiguous, as this isolated sub-catchment (Figure 5c) lies north of monsoon incursions in climate models (Jennings et al., 2015) and south of the likely westerly extent (see discussion and Parton et al., 2015b). Large spatial gaps in the palaeoenvironmental record coincide with an arid barrier in climate models (Figures 2 and 3). Collectively this indicates that climate systems remained separated, and that monsoons did not directly reach Mudawarra. Critically however, the mapped palaeohydrology indicates that a fluvial/lacustrine corridor could have crossed this arid barrier.

The Mudawarra catchment contains the Mudawarra and Tabuk sub-basins. Our mapping identifies, for the first time, the key role played by the Tabuk palaeodrainage system (Figures 4 and 5). The headwaters of the principal river of the Tabuk sub-catchment (Wadi Tabuk) originate just to the west of the Nefud (Figure 5c), transporting moisture northwards into the Tabuk sub-basin. Here, a palaeolake (Palaeolake Tabuk) formed in a sub-basin just south of the Mudawarra basin (Figures 4 and 5c). Wadi Tabuk is also complemented along its route by additional large tributaries from the Hijaz Mountains. The longest wadi feeding the Mudawarra sub-basin also flows from the south into the Mudawarra basin (Figure 4). Together these drainage systems provide a southern riverine connection between Mudawarra and the western edge of the Nefud sand sea. Furthermore, Palaeolake Tabuk and the Mudawarra depression are separated by a low sill, requiring only palaeolake depths of 15 m for water to overspill into the Mudawarra basin (see SI1 for detailed discussion). Sufficient rainfall at the latitude of the Nefud to activate the Tabuk River could therefore also have fed the Mudawarra palaeolake via Palaeolake Tabuk, creating a fluvial/lacustrine corridor between there and Wadi Nayyal (Figure 5c). Wadi Nayyal would have been active when precipitation formed palaeolakes in the Nefud, providing an access route from the Tabuk catchment to western parts of the Nefud dune field, from which the numerous interdunal lakes could easily be reached. Channels to the north of Mudawarra appear to have been much smaller, however, the largest of these connects with the Levant via Wadi Hisma, while others link to the catchment divide with the Al Jafr palaeolake basin (Figures 4 and 5). Collectively, these

palaeohydrological features would have formed a route from the Levant to the Nefud, if synchronously active. Given the pivotal role of the Tabuk palaeohydrology in creating these connections, this route is here termed the Tabuk Corridor.

### 3.1.3 Euphrates Corridor

The palaeohydrological data also suggests the possibility for another more circuitous route (Figure 4) via the River Euphrates, which flows through the northeastern part of this arid region. Activation of the Euphrates tributaries in southern Iraq and Kuwait is required to allow connection with the Nefud. Equally, if Wadi Batin (Figure 4) reached the Euphrates a connection would also have been established.

This paleohydrological analysis reveals the corridors which could have facilitated movements across the desert. To explore whether any of these were active between MIS 7 and 4, the catchment and hydrology data were linked with the palaeoenvironmental record. These data are discussed grouped by MIS, as higher temporal precision is rarely possible due to dating uncertainties. Where possible, more specific temporal and geographical clustering of palaeoenvironmental proxy data are outlined in the text. Results are summarised from detailed region-by-region discussions for each MIS provided in SI2-5.

### 3.2 MIS 7 (~243-191 ka)

During the MIS 7 interglacial, broadly contemporaneous enhanced humidity occurred in the Levant, northeast Africa, and northern Arabia (Figure 6, Table 1, and SI2). However, evidence for this humidity is spatially discontinuous, and possible connections between the Nefud and surrounding regions remain unclear.

At the catchment level, substantially enhanced Nile flow (sapropels S7 & 8) and humidity in local catchments (see Figure 6, Table 1 and SI2) suggest a route along the Nile to the Sinai Peninsula was open between ~200-194 ka and at ~220 ka (Williams et al., 2015). Although errors are broad, mean dates for palaeosol formation under humid conditions in the northeast Sinai also cluster around 190-200 ka (Roskin et al., 2013). Thus, opportunities to cross the Sinai are likely to have been available at this time, particularly if precipitation in the Negev dated to ~228-193 ka (Vaks et al., 2007, 2010; Waldmann et al., 2010; Figure 5b and 5c) was produced by southern migration of westerly rainfall. The synchronicity of southern Levantine, eastern Sinai and North African humidity therefore raises the possibility of dispersals out of Africa. In the coastal and central Levant, low  $O^{18}$  values in Pequin cave speleothems show three humid episodes to have occurred during MIS 7 (Bar-Matthews et al., 2003), two of which are synchronous with sapropel formation (198 ka, 220 ka, and 242-240 ka); similarly, speleothem formation occurred ~230-210 ka at Jerusalem West (Frumkin et al., 1999). Broad synchronicity of humidity across the wider Levant ~225-220 ka (Macumber, 2008; Frumkin et al., 2008; Gasse et al., 2015; Torfstein et al., 2015; also see SI2) may also have provided hydrological connections across this region and with Azraq (Figure 5a), although there is currently no evidence for hydrological connections further south into northern Saudi Arabia at this time. Likewise, potential humidity reported from Mudawarra during MIS 7 (Petit-Maire et al., 2002) appears unreliable (see SI2).

Palaeosols, and possibly lakes, formed in the Nefud dune field during this period (Figures 5b and 5c, Petraglia et al., 2012; Rosenberg et al., 2013), demonstrating that northern Saudi Arabia experienced some humidity during MIS 7. The Orontes catchment might have provided a bridge from the Levant to the Euphrates system during MIS 7 (Figure 6) based on interglacial incision along this system, and

humidity in the Yammouneh basin (Gasse et al., 2015), although this remains undated. Connections between the Euphrates and the Nefud cannot be demonstrated. Although widespread hydrological connectivity may have surrounded northern Saudi Arabia during MIS 7, potentially including connections with North Africa, the available evidence cannot therefore demonstrate palaeohydrological connections sufficient to connect these areas and the Nefud.

### 3.3 MIS 6 (~191-130 ka)

During MIS 6, periods of substantial connectivity between humid catchments occurring in many parts of the study region (Figure 7, Table 2 and SI3). At ~180-170 ka, humid climatic conditions prevailed across northeast Africa and the Levant (Figure 7). Sapropel S6 in the Mediterranean (Williams et al., 2015) indicates enhanced Nile flow at that time; in combination with lowered sea levels this may also have reduced Sinai-Levant crossing distances (see discussion and SI3). The northern Sinai may also have received moisture at this time, based on travertine deposition in the southern Negev (Waldmann et al., 2010; Figure 5b) dated to ~182 and 174 ka (Table 2), and error ranges for the aforementioned palaeosols from northeast Sinai also encompass MIS 6, although as means centre around terminal MIS 7 this may be their most likely formation period. These data suggest that population connections between the Sinai and North-east Africa could have occurred during MIS 6 (Figures 1 and 6), particularly during this early MIS 6 regional synchronous humid event. However, humidity in the southern Negev ceases after ~174 ka, indicating that this connection may have been short-lived (Figure 5b). Further north, data from the Dead Sea and central and northern Levant (Bridgland et al., 2012; Gasse et al., 2015; Torfstein et al., 2015) indicate humidity throughout MIS 6 (Figure 7). Speleothem records from the Soreq (Ayalon et al., 2002), Pequin (Frumkin et al., 1999) and Jerusalem West (Bar-Matthews et al., 2003) caves show significant humid periods between ~178 and 152 ka, and MIS 6 was generally wetter and cooler than the present day (which sees 550mm+ annual rainfall).

South-east of the Levant, lakes formed in the Azraq and Mudawarra sub-catchments (Petit-Maire et al., 2010; Cordova et al., 2013) during MIS 6 (Figures 5a and b). Lacustrine episodes at Mudawarra (~170 and 150 ka) show the central portion of the Tabuk Corridor to be open (Petit-Maire et al., 2010), although no northern Saudi Arabian humidity is documented, and thus the climatic source of moisture for Mudawarra remains unclear (cf. Parton et al., 2015b).

Given central and northern Levantine humidity, active hydrology in humid catchments could have connected the Levant and Euphrates (Figure 7). MIS 6 flow along the Euphrates itself (Demir et al., 2008) may have linked the Levant with the Arabian Gulf, when lowered sea levels would have resulted in the exposure of the Gulf as a plain bisected by the Ur-Schatt river; the sea-level low stand extension of the Tigris/Euphrates (Parker and Rose, 2008). Although a contiguous eastwards extension of the Euphrates Corridor may therefore have surrounded northern Arabia, it remains unclear whether any activation and penetration of tributaries from the Euphrates into the northern Saudi Arabian Desert was possible, given the lack of evidence for humidity in the Nefud (see Figure 7 and SI3).

### 3.4 MIS 6-5e transition and MIS 5e (~137-114 ka)

The MIS 6-5e transition and early MIS 5e (~137-120 ka) appears to be a key period when synchronous climatic amelioration initiated significant connections between the Levant and the Nefud via the Tabuk Corridor (Figures 5b, 8, 9, Table 3 and SI4). Documented humidity along the length of this route (Figures 3, 5, 8 and SI4) would have provided a contiguous freshwater corridor bridging the desert barrier shown in climate modelling for the 130 ka optima (Figure 9).

In addition, at the onset of the glacial-interglacial transition, when sea-level was low, dispersals across the northern Sinai may have been possible via modelled humid areas (Figure 9) and eastern branches of the Nile delta on the exposed shelf (*sensu* Horwitz and Tchernov, 1990; Figure 13). Furthermore, there is considerable evidence for increased humidity in the southern Negev at this time (Figure 5b, Vaks et al., 2007), probably due to a southward shift of the Mediterranean Westerlies (Figures 13 and 9, SI4). Shelves were removed by rising sea-levels during peak MIS 5e (~125 ka), yet this coincides with evidence from sapropel S5 (~125-118 ka) which indicates that the Nile received substantially enhanced flow (Williams et al., 2015) at a time of enhanced humidity throughout much of the Sahara (Drake et al., 2011) and the Negev (Figure 5b, Vaks et al., 2007; Waldmann et al., 2010), suggesting dispersals were still possible. In the northeast Sinai at least two discrete palaeosols formed between early MIS 5e and 5a, and late MIS 5e-5c (Roskin et al., 2011, 2013; Muhs et al., 2013), and as stabilisation periods are estimated to be approximately 10ka (Roskins et al., 2013), some of these soils may have formed during the latter part of the relatively humid MIS 5e. Terraces also formed along drainage of the southern Negev highlands proximal to the Negev/Arish divide sometime between mid-MIS 6 and early MIS 5e (172-124 ka, 2 $\sigma$ ), being incised by the end of MIS 5 (Faershtein et al., 2016). Given limited supporting evidence for southern Negev humidity during central MIS 6 (Figure 5), this terrace formation may relate to the MIS 6-5e transition, and imply that tributaries of the middle Arish and in southeast Sinai would have been active. Across the wider Levant, lake core and speleothem data (Figures 5a and 8, Table 3 and SI4) (Vaks et al., 2006; Gasse et al., 2015; Torfstein et al., 2015) indicate ameliorated conditions were present for much of the transition and MIS 5e, with a notable period of substantial regional humidity between ~128 and 122 ka. Enhanced humidity during this prominent event appears to be spatially continuous from the southern Negev to the northern Levant (Bar-Matthews et al., 2000, 2003; Vaks et al., 2007; Gasse et al., 2015; Nehme et al., 2015; Torfstein et al., 2015).

The aforementioned Negev humidity in the southern Dead Sea catchment (Figure 5b) during the transition could have facilitated movements into the northern end of the Tabuk Corridor, via Wadi Hisma (Figure 8), which is bracketed by humid catchments and contains drainage linking the Negev with the Mudawarra sub-basin of the Mudawarra/Tabuk depression. Around this time (Figure 5b) the Mudawarra sub-basin hosted a large palaeolake (Petit-Maire et al., 2010), although the origin of this moisture (African Monsoon vs. Red Sea convection) remains unclear (Parton et al., 2015). Palaeoclimate modelling (Figure 9) and dated Nefud palaeolakes (Figure 5b, Rosenberg et al., 2013) suggest moisture from the African Monsoon reached the southern Tabuk catchment during the transition and MIS 5e, and would thus have activated the headwaters of Wadi Tabuk, and fed (Figure 9) Palaeolake Tabuk, which lay only ~30 km from Palaeolake Mudawarra. Thus, regardless of the source for Mudawarra moisture, if the Tabuk sub-catchment was fed by the monsoons from the south, it would be active at the same time as the Mudawarra palaeolake during MIS 5e, thereby linking it and the Wadi Nayyal catchment of the western Nefud (Figures 5 and 9). Significantly, if climate models are correct and moisture did not directly reach Palaeolake Mudawarra at this time, the paleohydrology could explain how MIS 5e Palaeolake Mudawarra formed. The shallow, monsoon-fed Palaeolake Tabuk could have filled (see SI1 for detail) and cascaded into the Mudawarra basin, providing an indirect monsoonal source of moisture for the Mudawarra palaeolake. MIS 5e palaeolakes in the Nefud (Rosenberg et al., 2013; Scerri et al., 2015; Breeze et al., 2015) suggest activation of local drainage, such as Wadi Nayyal, would have completed the Tabuk Corridor (Figures 5, 9 and SI4) at this time. Collectively therefore, the hydrology discussed above would have connected the Levant and Nefud. The modelled extent of monsoon incursions also indicates the Nefud could have been connected to regions further to the south by monsoon moisture during peak MIS 5 (Figure 9).

The general overlap of dated proxies along this route occurs between 138 and 118 ka, highlighted by Figure 5b. To attempt to refine the spatio-temporal character of this connection, Figure 10 also displays timesliced kernel density maps for the transition and MIS 5e. Such evidence indicates that (within  $1\sigma$  errors) the MIS 5e Tabuk Corridor route was open between ~135 and 117 ka, and the greatest clustering of dates along the corridor at the  $1\sigma$  level suggests ~126-120 ka as the most likely period for contiguous connection (Figure 10). Population exchange across the Jordanian plateau could therefore have been possible for a window potentially as short as 6 ka around the transition.

Although the Azraq Corridor also contains palaeohydrological systems that could cross the potential arid region (Figure 5c), currently there is no evidence for MIS 5e humidity throughout this route, as moisture is only tentatively indicated (Cordova et al., 2013; Ames et al., 2014) in the westernmost end (Azraq) of the five sub-catchments along the corridor (Figure 5b, 8, and SI4). Climate models (Figure 9) and the boundaries of the Mediterranean westerlies (Figure 2) also dispute receipt of substantial moisture in the central reaches of the Azraq Corridor at this time.

Humidity in the Euphrates Corridor is contiguous (Figures 8 and 9) from the Levant to the northeast Mediterranean and likely the Orontes catchment (Bridgland et al., 2012; Gasse et al., 2015), facilitating access to the Euphrates. The Levant and southern Iraq may therefore have been connected, although access further south via the Ur-Schatt river and the Gulf Plain was likely removed after ~130 ka by sea level rise (Figure 8). Consequently, populations may have been able to move along the Euphrates Corridor, although climate modelling indicates monsoonal moisture did not reach the lower Euphrates, inhibiting direct connections with the Nefud (Figure 9). There is also a lack of evidence for hydrological activity in the southern Iraq desert (SI4), though this might be due to limited research in this area. The headwaters of Wadi Batin lie in areas likely in receipt of monsoonal moisture, so this system could potentially have provided a riverine link. However, as the system is severed by the undated Ad Dhana dunes it is unconfirmed whether downstream propagation would have been sufficient to allow it to connect the Nefud and Euphrates during MIS 5e (Figure 9).

### 3.5 MIS 5a (~85-71 ka)

Proxy data for the remainder of MIS 5 (SI5 and Table 4) provide an indication of a brief recurrence of Nefud-Levant connections via the Tabuk Corridor during MIS 5a (Figures 5 and 11).

During this time, it appears to have been possible to reach the Sinai from the Sahara. Sapropel formation at ~80 ka (S3, Williams et al., 2015) indicates substantially enhanced MIS 5a Nile flow and the Sahara experienced some humidity (Drake et al., 2013). Northern Negev speleothem formation (Vaks et al., 2006) and core data from the Dead Sea (Torfstein et al., 2015) both suggest an increase in precipitation at this time, and palaeosols in the northeast Sinai have dates broadly overlapping with MIS 5a (Roskin et al., 2013). In the southeast Sinai, dates for terrace formation along drainage straddling the Negev/Arish divide (Faershtein et al., 2016) and a terrace palaeosol at Nahal Lavan (Ben-David, 2003; Roskin et al., 2011) overlap with MIS 5a at two-sigma levels, although the bulk of these probability distributions lie in MIS 4. However, there is limited evidence from southern Negev speleothems (Figure 5a); potentially indicating Mediterranean precipitation did not move this far south at this time (see discussion). Sea level was however low for much of this period, exposing shelves (Siddall et al., 2003) and with a prominent low-stand around 75 ka (Lambeck et al., 2011). The evidence thus indicates the potential for crossing the northern Sinai at least, possibly via drainage extensions onto the wetter shelf and along Levantine rivers into the central Dead sea catchment.

Southeast of the Levant, dated lacustrine deposits (Figures 5b, and 11, Table 4) indicate that lakes formed in the Al Jafr (Macumber, 2008) and Mudawarra basins (Petit-Maire et al., 2010). In the case of Al Jafr, this likely resulted from the increased moisture in the central Dead Sea clipping the Al Jafr catchment divide, and feeding the basin from the west. Such an interpretation is supported by climate models (Figure 9), which also show the monsoon did not reach this area and thus is unlikely to be a water source. At present this western Al Jafr boundary receives ~200mm of rainfall and fluvial input into the basin only occurs after episodic storms (Mischke et al., 2015). These lake formation episodes in the western ends of the Tabuk Corridor coincide with palaeosol development in the Nefud (Table 4, Petraglia et al., 2012), and the likely monsoonal source of the Nefud humidity again suggests activation of the Wadi Nayyal and Tabuk catchment (Figures 5c and 12). These data may therefore indicate a reopening of the Tabuk Corridor via a more northern initial point than during 5e (green bar, Figures 5a and b). However, the evidence supporting this MIS 5a connection is less secure than for during 5e. The Al Jafr catchment is the weakest link, as this date has very large errors and minimal detail is published (Macumber, 2008). Furthermore, the Nefud palaeosol at Jebel Katefeh-1 (Petraglia et al., 2012; see also Groucutt et al., 2015d) could potentially relate to comparatively low levels of rainfall or to MIS 3 (although authors favoured MIS 5a).

Kernel density analyses (Figure 12) of proxy data spanning 5a shows that the most likely period for contiguous connection lies between ~82-70 ka, and that after ~70 ka no connection can be determined, with wide error ranges for Al Jafr and the Sinai palaeosols (Figure 5b) preventing further precision. As Al Jafr provides an important connection for dispersals, further research in the basin may be warranted to refine humid episodes and periods of occupation. Mischke et al. (2015) recently demonstrated that Al Jafr formerly held extensive shallow freshwater wetlands that date to ~MIS 3 based on radiocarbon methods, while cautioning that this could represent a minimum age. OSL dating of these deposits may therefore be of interest for confirming or refuting this potential MIS 5a corridor.

Elsewhere across the region, lake formation at Azraq (Cordova et al., 2013) also overlaps with MIS 5a (Figure 5a), but there is no other evidence for humidity in this corridor. Humidity in the central and coastal Levant (Frumkin et al., 1999; Bar-Matthews et al., 2000) continues into the northern Levant at Yammouneh (Gasse et al., 2015), and could potentially have provided access to the Orontes and Euphrates Corridor (Figure 11), but again no connections to the Nefud can be demonstrated.

#### 4. DISCUSSION

We now discuss these results in relation to regional palaeoclimate, opportunities for human dispersals, and the archaeological record.

##### 4.1 Regional climate systems and environments

Currently, the majority of the Arabian Desert belt is hyper-arid, receiving less than 100 mm of annual precipitation on average (Figure 2). Conversely, much higher levels of precipitation are found in the Levant (c. 300-1600mm), generated by the Mediterranean westerlies, which bring precipitation from the eastern Mediterranean during the winter months. Penetration of this moisture into the interior is limited, declining rapidly further south and east, however, further north the westerlies penetrate much further inland and arch southwards into Iran, bringing limited rainfall to the north-central Arabian peninsula, and the Hajar Mountains of Oman (Figure 2). Some increased moisture also reaches limited areas of southern Arabia; the Dhofar Mountains receive summer precipitation from the Indian Ocean Monsoon at the extreme northern limit of its current annual latitudinal variation (Figure 2), while the

Yemen highlands and Asir Mountains of southwest Arabia receive rainfall from the East African Monsoon during spring and autumn. The latter rainfall penetrates far enough northwards to coincide with the region of north-central Arabia that experiences westerly rainfall during the winter months, producing in combination an isolated semi-arid environment in north-central Arabia and semi-arid flora in the Nefud (Schulz and Whitney, 1985).

Episodically during the late Middle and Late Pleistocene, the spatial extents of local moisture sources altered substantially in response to orbital forcing of regional climate (Herold and Lohmann, 2009; Smith, 2012; Blome et al., 2012; Drake et al., 2013; Parton et al., 2015b). As discussed below, movement of the westerlies was modest. However, northward shifts in moisture availability, due to increased zonal transport (Herold and Lohmann, 2009) and/or movement of the Intertropical Convergence Zone (ITCZ) corresponding with solar insolation maxima, resulted in prominent monsoonal incursions which produced both ‘Green Sahara’ and ‘Green Arabia’ humid episodes (Drake et al., 2013; Parton et al., 2015b). While these events are prominent in interglacials, episodic increased moisture also occurred during MIS 6 and 3 (Parker, 2009; Parton et al., 2013, 2015b; Drake et al., 2013) and substantial variability between individual humid episodes and regions is also seen; for example, humidity in the Sahara and Arabia were sometimes synchronous, and sometimes asynchronous (Drake et al., 2013).

Our palaeohydrological data indicate that episodic increases in availability of freshwater associated with these climatic shifts may have provided specific opportunities for hominin populations to expand into previously unsuitable regions. In the Sahara, it has been shown that active palaeohydrology formed corridors that provided discrete opportunities to colonise and traverse the desert that were exploited by hominins and other fauna during the Holocene and MIS 5 (Drake et al., 2011). Here, Middle Palaeolithic stone tool assemblages exhibit spatially explicit patterns that correspond with these modelled palaeohydrological routes (Scerri et al., 2014a). In Arabia, recent analyses (Scerri et al., 2015; Breeze et al., 2015) have also demonstrated the frequent association of Middle Palaeolithic archaeological sites with preserved palaeolake deposits in the Nefud desert and with major palaeodrainage systems across the wider Peninsula. It is therefore likely that palaeohydrology also exerted a critical control on the spatio-temporal pattern of human dispersals in the Arabian Desert, although prior to our work little focus has been given on to how it may specifically have facilitated interregional dispersals. Whether archaeological evidence supports such movements is explored in subsequent sections, and a discussion of how mapped hydrology relates to Pleistocene climatic conditions and regional moisture sources is provided here (see also Parker, 2009; Drake et al., 2013 and Parton et al., 2015b for detailed syntheses of regional palaeoclimate).

Pleistocene Green Sahara events (Drake et al., 2011; Larrasoña et al., 2013) permitted populations to cross the Sahara, and hominins, likely *Homo sapiens*, were present in the Maghreb by MIS 6 (Smith et al., 2007b; Garcea, 2011). Palaeoclimate models and palaeohydrology (Scerri et al., 2014a) suggest environmental connections also existed between sub-Saharan Africa, the Maghreb and the Sinai during MIS 5, potentially facilitating dispersals to the east. Substantial increases in Nile flow documented by Mediterranean sapropel formation (Williams et al., 2015) may also have provided ‘Nile Corridor’ dispersal opportunities towards the Sinai (Van Peer, 1998), and six sapropels events (S9 to S3; Larrasoña, 2012) occur between MIS 7 and 5. While these indicate enhanced receipt of monsoonal moisture by the Nile and peak flow, the Nile also flows at lower intensities throughout much of the Pleistocene (Revel et al., 2010). From a hydrological perspective, therefore, African hominin populations had recurrent opportunities to reach the Sinai during the assessed period, and from there the Levant (and episodically Arabia), as indicated by the palaeohydrological maps.

Palaeohydrological and climatic data indicate the Sinai Peninsula was recurrently accessible from both the west and east. However, palaeoenvironmental data from the Sinai itself are extremely limited. Although major drainage systems of the peninsula have undergone channel modifications (Kusky and El-baz, 2000; AbuBakr et al., 2013; Gaber et al., 2009), limited radiometric dates hinder detailed estimates for when these systems were fluvially active. At present the westerlies bring limited precipitation to the northern Sinai, dropping rapidly from 200 mm at the coast, to below 50 mm within 50 km to the south (Enzel et al., 2008). Enzel et al. (2008) argue that there was no change to the southern boundary of this Mediterranean synoptic system during the Middle and Late Pleistocene. This argument is linked to evidence for hyper-aridity of the southern Sinai/Negev desert through the Quaternary (Amit et al., 2006), however considerable debate surrounds the extent of the Mediterranean westerlies in the past (e.g. Arz et al., 2003). Speleothems (Vaks et al., 2007, 2010, 2013) show that increased moisture occurred in the southern Negev (Figure 4) during MIS 7 and 5, potentially associated with southern movements of intensified westerlies. Palaeoclimate modelling (Scerri et al., 2014a; Coulthard et al., 2014; Jennings et al., 2015) shows a substantial increase in moisture in the northern Sinai during MIS 5e. Rainfall of between 200 and 300 mm annually in two narrow bands on either side of the northern Sinai would have reduced distances between contemporary savannah biomes (Scerri et al., 2014a) to less than 100 km (Figure 13). This appears supported by evidence for fluvial activity and palaeosol formation in the northeast Sinai during MIS 5 (Ben-David, 2003; Roskin et al., 2011, 2013; Faershtein et al., 2016). The palaeoclimate model also suggests this increased moisture to continue along the North African coast, and evidence from Morocco (Jacobs et al., 2012) and Tunisia (Causse et al., 2003) indicates that much of Africa north of the Sahara experienced enhanced humidity during MIS 5, presumably due to westerly rainfall. This was also the case in the early Holocene (e.g. Swezey et al., 1999), and presumably during other interglacials. Thus, these periods of increased moisture availability could have facilitated movements across the northern Sinai, as only a short arid barrier existed (Figure 13).

Crossing the Sinai could also have been facilitated by migration of Nile delta channels to the east, as was the case in historical times with the pelusiatic branch (Sneh and Weissbrod, 1973) (Figure 13). If a similar channel migration occurred in MIS 5e, the climate model suggests a reduction in crossing distances between the semi-arid areas of the Sinai to just less than 50 km (Jennings et al., 2015). Furthermore, even today the Sinai receives 200 mm of annual rainfall at the coast, decreasing to 50 mm ~50 km inland (Enzel et al., 2008). During glacials, exposed coastal shelves would have been further north, thus receiving higher rainfall and facilitating connections, with Horwitz and Tchernov (1990) suggesting the extension of eastern Nile delta channels and Levantine drainage systems onto the exposed coastal shelves at these times, which would have reduced migration distances (Figure 13), again facilitating crossing. They propose that the hippopotamus used this mechanism to disperse from Africa to the Levant at the end of the last glacial, suggesting that animal dispersal was possible even under adverse climate conditions. Large mammalian dispersals eastwards from Africa during the Pleistocene have been studied in detail and appear to have occurred, but not in great numbers (compare Tchernov, 1998; O'Regan et al., 2005; Finlayson, 2009), however the presence of numerous paleoarctic animals in North Africa (e.g. Kingdon 2005), so much so that the paleoarctic biome extends across all Africa north of the Sahara, may highlight the accessibility of the Sinai. Perhaps most significantly, as the distance across the Sinai is relatively short, even very brief influxes of moisture, such as occasional seasonal storms, could have produced ephemeral water sources, potentially permitting limited hominin population exchanges. To provide perspective, the Sinai Peninsula is only ~200 km across at its widest point; in 2013 a marathon runner crossed the central peninsula in 3 days while fasting for Ramadan (Bocchialini and El Gazwy, 2014), and recent aboriginal desert nomads have been credited with journeys covering greater distances in only three days (Cane, 2013).



The Levant is the physiographic gateway between the Sinai, Arabia and the rest of Eurasia, displaying a broad pattern of comparatively higher humidity during both glacials and interglacials compared to the regions to the south, east and west (Lisker et al., 2010; Frumkin et al., 2011). The Mediterranean coast of the Levant is wetter than much of the surrounding region, even today, experiencing in excess of 550mm annual rainfall (Bar-Matthews et al., 2003). During various periods of the late Middle and Late Pleistocene rainfall in the Levant was more plentiful in these areas, linked to enhancements of the westerly system (Bar-Matthews et al., 2000, 2003; Ayalon et al., 2002). Increased rainfall is recorded in the dated speleothems along the eastern Mediterranean coastal region (from Soreq and Pequin caves) which show extreme  $\delta^{18}\text{O}$  minima reflecting enhanced humidity exceeding current levels during humid episodes of MIS 7, 6 and 5 (Bar-Matthews et al., 2000, 2003; Ayalon et al., 2002), and produced the mapped humid catchments in these areas. In the central Levant, glacial phases were periods of generally enhanced moisture; however, the wettest episodes to the north occurred under interglacial conditions (Figures 6, 8 9 and 11, and Gasse et al., 2015; Nehme et al., 2015). This may relate in part to a southern displacement of the Mediterranean westerlies during glacials due to expansion of Eurasian ice sheets producing drier, steppic conditions in the northern Levant during these periods (Gasse et al., 2015). The extent of displacements of the southern boundary of the westerlies is, however debated. The southern Negev (Figure 13) is a critical area in this debate, and is hyperarid in the present interglacial. However, short-lived humid intervals occurred here during the Pleistocene (Vaks et al., 2007, 2013; Waldmann et al., 2010; Torfstein et al., 2015), termed 'Negev Humid Periods' (NHPs; Vaks et al., 2007, 2010); two of which occur during the period focused upon here; NHP2 (~225-190 ka), and NHP1 (~142-109 ka) (Figure 5). Considerable debate surrounds the source of this moisture. Waldmann et al. (2010) interpreted this humidity as indicating southern tropical (i.e. monsoonal) moisture reaching the Negev, and evidence from the Dead Sea has also been interpreted as reflecting the interplay of both monsoon and Mediterranean moisture (Torfstein et al., 2015). However a steep north to south gradient of decreasing speleothem thickness in the Negev does not support the theory of direct incursion of southern monsoons into the Levant (Enzel et al., 2008; Vaks et al., 2010, 2013), fuelling arguments that NHPs were instead caused by southern shifts of westerly rainfall (Vaks et al., 2010); a view considered more parsimonious here, given present data. The speleothem evidence also indicates that substantial westerly rainfall did not reach much further south than the southern Negev during these periods, and hence did not penetrate northwest Arabia.

In the Arabian Peninsula, the precise northern limit of moisture during ameliorated periods remains unclear (Figure 2). Monsoon incursions during MIS 11, 9, 7, 5, and 1 provided sufficient rainfall to produce lakes and wetlands in the Rub' al Khali, Oman and Nefud deserts (e.g. Schulz and Whitney, 1986; Wellbrock et al., 2011; Petraglia et al., 2011, 2012; Rosenberg et al., 2011, 2012, 2013; Crassard et al., 2013a, 2013b; Matter et al., 2014; Hilbert et al., 2014), initiate fluvial activity in the hinterlands of the Oman mountains (Blechs Schmidt et al., 2009; Parton et al., 2013, 2015a) and speleothem growth in southern Arabia (Burns et al., 1998; Neff et al., 2001; Fogg et al., 2002; Fleitmann et al., 2003). Until recently, the general view was that the Indian Ocean Monsoon was the source of moisture during these wet episodes. However, climate modelling (e.g. Herold and Lohmann, 2009; Jennings et al., 2015) indicates that moisture across much of Arabia, including the Nefud, is related to a substantial north-eastwards intensification of the African summer monsoon (Figure 2). This may have been augmented by strengthening of convective storms from Red Sea synoptic troughs in northern Arabia (Rosenberg et al., 2013; Parton et al., 2015b) and possibly also by intensification of the Indian Ocean Monsoon in some areas of southern Arabia (Burns et al., 1998; Neff et al., 2001; Fogg et al., 2002; Fleitmann et al., 2003). The existence of the large Palaeolake Mudawarra, in the southern Jordan highlands may reflect the northern extent of monsoonal moisture (e.g. Petit-Maire et al., 2002- grey dashed line in Figure 2). However, this point remains controversial (cf. Parton et al., 2015), and climate modelling and the

Levantine speleothem patterns instead suggest that a considerable arid barrier was present across much of northern Arabia during MIS 5e (Jennings et al., 2015), (Figure 2). Currently, there are gaps of 170 km between the southernmost Levantine proxy records (Figure 3) and Mudawarra, and then of 380 km between the Mudawarra basin and the northernmost dated site in the Nefud (Rosenberg et al., 2013), collectively coinciding with this modelled arid region. In conjunction with the Levantine data, this lack of palaeoenvironmental archives in northern Arabia and ambiguity in the source of Mudawarra moisture (e.g. the westerly vs. monsoonal rainfall, or a Red Sea source) inhibits confirmation that continuous climate amelioration covered this area (as discussed by Parton et al., 2015b). Nonetheless, despite this ambiguity, and evidence for an arid barrier (Figure 2), our results support hypotheses of demographic connection (Parton et al., 2015b), by indicating that the Tabuk Corridor would have provided a spatio-temporally specific opportunity for hominins to cross between the Levant and northern Arabia.

Opportunities for hominin movements between the Levant, Africa, and Arabia were probably controlled by the climatic shifts discussed here. In addition, perennial fluvial systems such as those that flow along the Nile and Euphrates corridors would have made some areas accessible throughout much of the late Middle and Late Pleistocene. The adjacent Euphrates and Orontes systems represent possible dispersal routes that were viable for much of the Pleistocene, although directly dated archaeological evidence remains sparse. The Orontes terraces have been correlated to marine isotope stages through a combination of direct dating and uplift modelling (Bridgland et al., 2012), and chronologies of terraces and palaeosols in the Euphrates have been inferred from their positions relative to Holocene sediments and dated Pleistocene/Pliocene basalts (Kuzucuoglu et al., 2004; Demir et al., 2007, 2008). New data from the Yammouneh core (Gasse et al., 2015), from a basin within the greater Orontes catchment, also indicate humid climatic conditions during MIS 7, 6, 5e and 5a. The available evidence shows that both of these important fluvial systems flowed throughout most of the Pleistocene, with aggradation and terrace formation during glacials, and incision and high flow during interglacials (Demir et al., 2008), thus providing potential corridors for dispersal. However, dispersals distant from these perennial fluvial systems (Figure 1) and into or across the desert of northern Arabia would have been dependent on the activation of palaeohydrology within the desert as a result of climatic changes.

In summary, when humidity was temporally synchronous in northeast Africa, the Levant and Arabia, it has been suggested that this climatic amelioration could have provided opportunities for hominin dispersal into Arabia. For example, it has been hypothesized that enhanced southern climate systems brought moisture into the Levant, producing ameliorated semi-arid climatic conditions throughout much of the region permitting hominin dispersals from Africa into the Levant and onwards into Arabia during MIS 5e (Vaks et al., 2007; Waldmann et al., 2010; Frumkin et al., 2011; Parton et al., 2015b; Torfstein et al., 2015). However, the aforementioned Levantine speleothem deposition patterns indicate overlap between the westerlies and southern moisture sources was minimal or non-existent (Enzel et al., 2008; Vaks et al., 2013), supporting the presence of the modelled arid barrier across northern Arabia (Figure 2). To confirm the potential for population exchange, even if conditions were more ameliorated than climate models indicate, it is still necessary to determine whether populations could move across the region while in proximity to confirmed freshwater locations. Our palaeohydrological data provide this assessment, and indicate that several spatio-temporally specific opportunities for dispersal may have existed during late MIS 6 and MIS 5. Given these opportunities, the question therefore becomes, does the archaeological record support hominins actually crossing this region, and if so via which route, at which times, and from which potential source locations?

#### 4.2 Archaeology and palaeohydrological dispersal opportunities

The widespread distribution of Middle Palaeolithic sites across the region examined here (Figure 1) indicates extensive hominin occupation during the late Middle - Late Pleistocene. However, there are relatively few well dated sites available to refine the timing of these events. It is also important to reiterate here that inevitably sampling bias may have influenced the distribution and quality of data that we have in the relatively understudied area of northern Arabia. Notwithstanding this, there is a dense concentration of sites across the Levant, and a line of sites identified by prior surveys emanates from this area along the Tabuk Corridor, and in the Nefud is complemented by sites identified by our own work (Scerri et al., 2015, Petraglia et al., 2012, and forthcoming papers). This pattern may be consistent with dispersal between the Levant and Arabia during the Mid-Late Pleistocene. Palaeoclimate results from the Euphrates Corridor indicate that routes skirting the region were sometimes available; however, there are no known sites along the Euphrates itself, and only a few in southern Iraq, thus little evidence that this corridor was used. A humid connection from the Levant to Arabia via the Azraq Corridor (Cordova et al., 2013, Ames and Cordova 2015) cannot be demonstrated at present (Figure 5a), and comparatively few sites are reported from central regions of this route. Therefore, of the potential routes into Arabia (Figure 1 and 5c), only the Tabuk Corridor currently shows evidence for both humidity and archaeology along its length. Furthermore, Figure 14 demonstrates that, at the catchment level, there is a comparatively greater density of reported sites along this route than the alternatives, supporting it as having been a significant avenue for population exchange between the Levant and Arabia during the Mid-Late Pleistocene. Results also suggest that opportunities to cross the northern Sinai may have existed under both glacial and interglacial conditions, facilitating hominin movements out of Africa demonstrated by the fossil record.

Consideration of dated archaeological sites, and the characteristics of excavated lithic assemblages, allows further elaboration of these observations. During MIS 7 (Figure 15), central Levantine ‘early Middle Palaeolithic’ archaeological sequences at sites such as Tabun, Hayonim and Misliya demonstrate a hominin presence (e.g. Bar-Yosef and Meignen, 2001; Shea, 2003, 2013; Valladas et al., 2013). Core reduction in the Levantine early Middle Palaeolithic is primarily unidirectional and bidirectional, resulting in high frequencies of blades and points. Distinctive retouched forms include retouched points, endscrapers, and burins (e.g. Shea, 2013). While dating of sites in the southern Levant has proven difficult, the MIS 7 date of Rosh Ein Mor (Rink et al., 2003), and the presence of other typologically similar sites in the area (e.g. Shea, 2003) suggests human occupation occurred in MIS 7. Collectively, these data may indicate a trans-Levantine dispersal of hominin groups that was facilitated by active drainage in adjacent catchments (Figure 15) that reached sites such as Hummal (Le Tensorer et al., 2007) in the Syrian Desert (Shea, 2013). While the latter populations may have been able to reach the Euphrates (Figure 15), archaeological evidence is currently too limited to confirm movements further along the Euphrates Corridor to the east. The site of Rosh Ein Mor (Figure 15) lies at the Wadi Arish/Dead Sea interface (Figure 4), suggesting that hominins could have penetrated the Sinai during MIS 7 (Rink et al., 2003). Yet, it remains unclear whether demographic connections could have occurred between Levantine and northern African populations via the Sinai at this time. Likewise, though hominins were present in both the Levant and Nefud (Petraglia et al., 2012), a connection between the two regions cannot be demonstrated by the palaeohydrological data. The MIS 7 lithic assemblage at JQ-1 is of Middle Palaeolithic character, but is small and of limited value for comparative analyses.

The extensive active palaeohydrology during MIS 6 indicates that this period may have been significant for hominin dispersals. Dated archaeological sequences in the Levant at Zuttiyeh, Neshar Ramla, Misliya, Hayonim and Tabun (Figure 16) demonstrate lithic assemblages appearing to span an important transition between the ‘early’ (i.e. ‘Tabun D’ in the traditional terminology) and ‘middle’

(‘Tabun C’) Middle Palaeolithic (see Groucutt et al., 2015b and references therein). Sites dating to the earlier part of MIS 6 are similar to earlier Levantine MP sites, and are characterised by unidirectional reduction (variably Levallois) and the presence of retouched points. The later part of MIS 6, such as at Neshar Ramla and Hayonim upper E, sees lithic assemblages more similar to those normally associated with MIS 5. Core reduction in the latter is Levallois dominated, with centripetal methods of both recurrent and preferential form being dominant (Groucutt et al., 2015b). The hominin species present at this time remain unclear. A fossil individual (C1), generally considered to be Neanderthal, was discovered at Tabun and may date to MIS 6 (Dennell, 2014). Tabun Cave is, however, taphonomically complex and chronometric dating of the sites has proven difficult with contradictory results (e.g. Hovers, 2009). The Tabun C1 fossil may suggest an MIS 6 presence of Neanderthals in the Levant and support a model where Neanderthal repeatedly moved south during glacial periods and *Homo sapiens* moved north out of Africa during interglacial periods. Other fossils from this period such as Zuttiyeh were not excavated using modern methods, are poorly dated and not well described due to poor preservation. Finally, an important fossil is Skhul IX, a *Homo sapiens* skeleton, which may be older than the other fossils from this site, perhaps dating to ~140 ka (Grün et al., 2005). Unfortunately, the excavation of the site in the early twentieth century, using methods that would be considered basic today, has made understanding the site formation processes and chronology difficult. It is possible that all of the occupations date to MIS 5e. A parsimonious reading of the available data is considered to be that an unknown hominin species was present in the earlier part of MIS 6, while the dispersal of *Homo sapiens* into the Levant began in MIS 6, but is most clearly expressed in MIS 5 (Skhul and Qafzeh). In lithic terms, several late MIS 6 Levantine assemblages demonstrate similar lithic characteristics, such as a focus on centripetal Levallois reduction, more commonly associated with MIS 5 sites (Groucutt et al., 2015b).

MIS 6 potentially yielded opportunities to cross the Sinai, which may have facilitated early hominin dispersals out of Africa, but dated sites are limited solely to the Levant (Figure 16). At this time, northern portions of the Tabuk Corridor were active and limited penetration of the northern Arabian Desert may therefore have been possible, however, no evidence has been recovered for either archaeology or humidity in the Nefud (Figures 5b and 7). MIS 6 Levantine populations also had the palaeohydrological (Figure 7) opportunity to disperse along the Euphrates Corridor, and potentially south to the Ur-Schatt valley and the exposed Arabian Gulf shelf, the site of the posited Pleistocene ‘Gulf oasis’ (Rose, 2010). However, an absence of archaeological sites or fossil material in the region to confirm such dispersals means this also remains speculative.

The Tabuk Corridor appears active during the MIS 6/5e transition, 5e and possibly MIS 5a, linking the Sinai, Levant and Nefud. Potential MIS 5 archaeological connections raise the possibility that human groups originating in either the Levant or Africa (or both) may have reached the Nefud during this period. Though there are no dated sites within the central Tabuk Corridor (Figure 17) there has been enough lithic analysis in the Levant and the Nefud to start to evaluate similarities and differences between lithic assemblages at its start and end. In the Levant, it appears that the constellation of technological features beginning in late MIS 6 and described above, continued into MIS 5. These assemblages have traditionally been described as the ‘Tabun-C’ facies of the Levantine Middle Palaeolithic, and are best known from MIS 5 sites (Figure 17) such as Skhul and Qafzeh (e.g. Shea, 2003; 2013; Hovers, 2009; Groucutt et al., 2015b). While further work is needed to understand variability, some basic observations and patterns can be discerned. The key focus of described assemblages is an emphasis on centripetal Levallois methods of core preparation and reduction. This has best been described at Qafzeh Cave (Figure 17) where most reduction seems to have been conducted with a recurrent centripetal Levallois method, supplemented by a preferential method late in the

reduction process (Hovers, 2009). While factors such as the levels of bidirectional reduction and the production of points vary somewhat, the basic centripetal Levallois focus of MIS 5 Levantine sites can be contrasted with the laminar and unidirectional-convergent foci of the Early and Late Levantine Middle Palaeolithic respectively. Aside from Qafzeh, broadly similar lithic assemblages have been recovered from the length of the Levant, from S-20 in the south, via Skhul, Naame, Nahr Ibrahim, Ras el Kelb, and extending into the Syrian interior at sites such as Hummal, Douara, and Umm el Tlel (Figure 17) (Shea 2003; 2013; Groucutt et al., 2015b). However, despite the Euphrates Corridor (Figure 17) being open during MIS 5, an absence of archaeological data prevents conclusions about whether Levantine populations exploited it.

Several sites dating to MIS 5, featuring artefacts with similar technological features to contemporary Levantine assemblages, have been identified in the Nefud (Figure 17). These include the sites of Khall Amayshan-1 (KAM-1, ~120-100 ka; Rosenberg et al., 2013; Scerri et al., 2015) and Jebel Umm Sanman-1 (JSM-1, MIS 5; Petraglia et al., 2012) and Jebel Qattar-1 (JQ-1, ~75 ka; Petraglia et al., 2011, 2012) at Jubbah. It is important to note that there are ambiguities when comparing lithic technologies. For example, the material from JKF-1 includes Levallois points with unidirectional convergent preparation, similar in some regards to Levantine late Middle Palaeolithic assemblages dated to MIS 4 and 3 (e.g. Groucutt, 2014). However, Levallois points have been found in some phases of the MIS 5 Levantine Middle Palaeolithic, such as layer XV at Qafzeh Cave (Hovers, 2009). Comparison may also be drawn with Levallois material in the MIS 5 layers of the Levantine site of Nesha Ramla (Zaidner et al., 2014). Ongoing research is clarifying the chronology of the Arabian Middle Palaeolithic, and increasing the number and size of known lithic assemblages. In terms of overall patterns of lithic similarities it appears that the Nefud sites display many similar typo-technological features to contemporaneous Levantine sites, from which connections between the two regions, perhaps via the Tabuk Corridor, can be envisaged (Figure 17). The focus on centripetal Levallois technology at both ends of the Tabuk Corridor during MIS 5, when knappers could have chosen to employ a wide number of alternative approaches, is parsimoniously viewed as indicating that the assemblages were made by related groups.

Dispersals between Africa and the Levant may have been possible during the MIS 6-5e transition via the Sinai, perhaps explaining the earliest evidence for hominins in the Levant at this time, or soon after (Grün et al., 2005). However, the breadth of proxy dates mean that while humidity occurred in the Sinai during MIS 5 (hence catchments are shown as humid in figure 17), we cannot conclusively determine during which substage. There are two locations in the northern Sinai that could relate to MIS 5 - as illustrated lithics appear similar to those from dated MIS 5 sites - the sites of A-306 (Gilead, 1984) and Ouadi T'Mila (Henry and Goldberg 1975) (Figure 17). More significantly, the Negev site of S20 (Kobusiewicz, 1999; Kobusiewicz et al., 2001) lies at the interface between the Sinai, Negev and Tabuk Corridor with minimum ages of ~80-60 ka for redeposited lithics that appear to date to MIS 5 and are again technologically similar to those of other dated MIS 5 sites, and correspond to the documented southern Negev humid episodes (Figure 17).

While an increasingly complex picture, the above data suggest a significant cultural (technological) dichotomy between assemblages dating to MIS 5 (and late MIS 6) and those dating to either side of this period. The early and late Middle Palaeolithic both see lithic assemblages in the Levant which are unlike those in northeast Africa at the same time. In contrast, in MIS 5 broadly similar lithic assemblages – with a particular focus on centripetal Levallois methods (for a wider discussion see Groucutt et al., 2015b) – are from across a wide area from East Africa, Arabia, the Levant and as far east as India. The existence of similar technologies in Arabia and the Levant at this time therefore fits a broader pattern

of greater connectivity between populations, correlating with the environmental amelioration of MIS 5. Much more work remains to be done in terms of quantitative comparisons of African and southwest Asian assemblages in order to elucidate the precise demographic and behavioural dynamics of this period (e.g. Scerri et al., 2015b)

#### 4.3 Traversing the Tabuk Corridor

Overall, archaeological observations underline the potential for MIS 5 connections between the Nefud and the Levant, which the hydrological data suggest could have originated via the Tabuk Corridor during MIS 5e and possibly 5a. To assess how viable movement along these routes was at the human, rather than catchment, scale, Figure 18 displays distances from mapped water sources (both drainage and lakes/marshes) along the MIS 5e and 5a corridors, accounting for topography using GIS path distance calculations. It should be noted that these are conservative estimates, as we display rivers only once they have reached >1000 km<sup>2</sup> upstream area, this means that headwater points of plotted rivers will not reach the catchment divide (due to the data cell size, they will always originate at a point where 31.62 km of cells lie upstream- although this may equate to a shorter straight line distance to the catchment divide). Minor headwater activation likely also occurred during humid phases. From the Negev to the Nefud along the MIS 5e corridor, the largest gap to be crossed between major sources is ~35 km between the southern Negev and Aqaba areas of the Dead Sea, followed by the Hisma-Mudawarra divide (~20-25 km). From Mudawarra however, hominins could potentially reach and occupy the Nefud (or vice-versa) without any gap of greater than 15 km between major sources, and generally while remaining within 5 km of water. During MIS 5a, exiting the Dead Sea would again be the largest gap (~45 km), followed by bridging the Jafr-Mudawarra divide (~25 km). This gap could however have been much larger (~80 km) if Al Jafr was only fed by moisture in the immediate west of the catchment, preventing drainage forming southeast of the basin wetlands. From Mudawarra to the Nefud, proximity to water may again have been easily maintained (Figure 18). Distance calculations rarely exceed 5-10 km in both the southern and western Nefud, supporting prior suggestions of widespread connectivity across the Nefud during humid periods of MIS 5 (Breeze et al., 2015).

The distance calculations provide an indication of the maximum density of major water resources within the regional landscape. The faunal and chronological evidence from the Nefud is presently somewhat contradictory (see Thomas et al., 1998; Rosenberg et al., 2013), but nevertheless suggests year-round freshwater availability during MIS 5. However, not all of these mapped features were necessarily active at the same time, and the quality of the water (i.e. ranging from fresh to strongly brackish) probably varied significantly according to seasonal evaporation effects. Such details can only be determined through field investigation of mapped features, where an indication of water quality can be obtained from palaeoenvironmental proxies such as fossils of non-marine molluscs and ostracods, since the ecological tolerances of extant species are often sensitive to salinity and other variables. Consequently, long-distance mobility in response to fluctuating water availability could have substantially facilitated dispersals into, and exploitation of, the semi-arid to savannah environments of northern Arabia along the routes here defined, and may have been a defining characteristic of populations in these regions.

Finlayson (2014) hypothesized high mobility 'rain-chasing' as a Saharo-Arabian hominin adaptive strategy; i.e. for groups to have been reactive to indicators of distant freshwater and to have rapidly travelled substantial distances to exploit this resource. The scale of annual, seasonal or even daily ranges amongst Pleistocene hominins remains unknown, and caution should be exercised when making ethnographic comparisons (cf. Kelly, 2014). Nonetheless, broad inferences can be made from ethnography of people living in similar environments, and anthropological observations of forager

groups in desert or semi-arid environments having maximum seasonal ranges varying from ~150 km to 1600 km may highlight the potential orders of magnitude for seasonal rounds, and that substantial variability could also be present during the Pleistocene. Breeze et al. (2015) noted that variability in the level of spatial tethering of hominin occupations to freshwater in these regions is likely to have been present throughout the Pleistocene in accordance with behavioural, technological, and evolutionary adaptive responses to freshwater fluctuations. Kelly (2014) also notes variation in strategic responses to freshwater fluctuations amongst recent water-tethered desert foragers, in accordance with local geomorphological and environmental factors. Such strategies include hierarchical exploitation of water sources in ascending order of reliability, and seasonal variation in foraging ranges in accordance with freshwater availability in the wider landscape (Kelly, 2014). Therefore, as part of large seasonal ranges, remnant water locations such as lakes and wetlands, springs, or pans that held water for prolonged periods, may have formed essential refuges that groups withdrew to during the dry season, after exploiting wider areas when rains permitted, as amongst recent aboriginal groups (Smith, 2013).

It is also possible populations were not as tightly tethered to primary river channels during periods of peak flow, if minor tributaries were also active, and immediate proximity to major rivers presented hazards. This is particularly the case for permanent trans-desert allogenic systems such as the Euphrates and Nile. For example, Kuper and Kröpelin (2006) indicate an absence of occupation along the immediate confines of the Nile valley during the Early Holocene humidity optimum, hypothesised to be due to the hazards of flooding and marshlands and a preference for grasslands over dense woodland. Their analyses imply an inverse relationship between peak Nile flow and dispersals along the immediate valley. This persistent trans-continental major allogenic system differs environmentally and volumetrically from drainage in the Arabian Desert activated during humid periods, although localised flooding could potentially have been a hazard here also. Even under such conditions, the catchment level approach highlights humidity in the wider catchments and adjacent regions, indicating less hazardous tributaries would also be active and that occupation and traversals could still have been possible.

An increased knowledge of the distribution of springs and very shallow groundwater would be useful for further understanding accessible freshwater across the region. Springs were an important aspect of Levantine and Syrian hydrological systems during the Pleistocene, (e.g. Macumber, 2008 and Por, 2004), even fuelling some rivers (Wagner 2011), however across the northern Arabian Desert barrier their occurrence appears limited. Aquifers in the Mudawarra, Tabuk and Al Jafr basins lie tens to hundreds of metres below the surface (Wagner, 2011) and we are aware of no spring discharge in these areas; in northeast Wadi Sirhan and Azraq in contrast, discharge from shallow aquifers has continued until recently (Wagner, 2011; Ames and Cordova, 2015). Pleistocene springs could have been important freshwater sources and possible refugial areas during climatic downturns (Ames and Cordova, 2015), however southeast of Azraq at present there is little published data regarding their distribution. To the south, many of the most potable springs of Arabia are associated with aquifers beneath major wadi courses (Alsharan et al., 2001). These recharge through infiltration of runoff into thick alluvial wadi bed sediments, discharge as springs lower down wadi courses (Wagner, 2011), and are highly responsive to water table elevations (Alsharan et al., 2001), such as those induced by substantial increases in regional precipitation. Consequently, during humid periods, or following a time lag after recharge during these episodes, springs may have provided freshwater resources along mapped drainage even under conditions of more ephemeral or discontinuous flow. Across the northern Arabian Desert near-surface groundwater levels during former humid phases remain largely unknown, and historically reported occurrences of very shallow (i.e. hypothetically accessible to Pleistocene hominins) groundwater centre on endorheic depressions that also hosted wetlands or lakes during periods when

enhanced precipitation elevated groundwater levels (such as Tayma or Jubbah- Engel et al., 2011; Petraglia et al., 2012) and which have been identified by the mapping. It should be noted that wetlands could still form in such basins even if precipitation increases were insufficient to create expansive lakes (e.g. Mischke et al., 2015). In the Nefud itself, any groundwater lies below the level of interdune floors, evidenced by an absence of present sabkha. However, during humid phases elevated localised lenses of groundwater created by the enhanced precipitation and infiltration from adjacent dunes may have resulted in the formation of the palaeolakes observed in the region.

Collectively, these data suggest that even considering underground and artesian water, and scenarios of moderate, rather than intensely enhanced precipitation, the mapped palaeohydrological features would still have been the most likely loci for fresh water. The high number of lake/wetland features and drainage systems mapped across northern Arabia, in varied geomorphological settings, may therefore have provided a diversity of water resources of varying annual longevity, and multiple options for ‘stepping through’ the desert or semi-arid landscape (*sensu* Smith, 2013), permitting highly mobile hominin groups to deal with moderate levels of environmental stochasticity. Although data indicates occupation of the Arabian Desert occurred during the late Middle - Late Pleistocene, such stochasticity means lifeways may not have been entirely comfortable, as groups may have been forced to sacrifice foraging efficiency in exchange for increased freshwater security (see Kelly, 2014).

## 5. CONCLUSIONS

In desert regions, the availability of freshwater is a critical controlling factor constraining human migration. The catchment-level analyses of palaeohydrological mapping presented here indicate that contiguous freshwater environments episodically connected the Levant and northern Arabia during the late Middle and Late Pleistocene. Estimates regarding hominin dispersals out of Africa based on genetic evidence remain ambiguous, affording an important role to synthetic studies incorporating palaeoenvironmental and archaeological data such as this one in order to generate testable hypotheses relating to the timing and extent of hominin dispersals. We emphasise that while we have identified one potential corridor between the Levant and Arabia showing support from the archaeological and environmental records and facilitated by the local distribution of water, we do not suggest this to be the only route that would have been utilised for such movements. Continued testing of this hypothesised dispersal route (and of others which currently show reduced evidence) through further palaeoenvironmental and archaeological field survey will therefore be an important priority for future work.

The analyses conducted here have determined the distribution of surface palaeohydrology in the northern Arabian landscape, refining our understanding of the palaeoenvironmental and archaeological records and identifying opportunities for dispersal into and across the deserts of this vast region. Critically, we have identified two periods, MIS 5e and 5a, during which hominins would have had the opportunity to disperse along the Tabuk Corridor into northern Arabia. Despite also being considered a wetter period in Arabia, at present data are insufficient to support any MIS 5c connection (SI5). Both MIS 5e and 5a corridor events are synchronous with brief periods of enhanced humidity in the north-central Dead Sea (Torfstein et al., 2015) that may also have provided connections to the central Levant and northern Sinai Peninsula. Based on present data, the Tabuk Corridor appears the most likely terrestrial route by which hominins and other mammal species could have dispersed into Arabia during the penultimate interglacial/glacial transition while remaining in proximity to critical freshwater resources. The dominant NW-SE orientation of drainage, wetland, and lake systems along this route (Figure 10) suggests that migrations would have been channelled by the distribution of water sources



in directions encouraging connection between the two regions. The spatial distribution and density of archaeological sites in the region also supports the Tabuk Corridor as having been a key avenue of dispersal for Middle Palaeolithic hominin occupations in the region (Figure 14).

Our palaeohydrological model therefore suggests that hominin populations in the Levant or North Africa had the opportunity to cross the northern Arabian Desert and reach the Nefud broadly contemporaneously with the occupations at Skhul and Qafzeh in the Levant, challenging the view that the earliest *Homo sapiens* populations were restricted to the Levant in a ‘failed dispersal’. A possible recurrence of palaeohydrological connectivity in the Tabuk Corridor during MIS 5a may also indicate that Levantine hominin populations were able to move across the northern Arabian Desert during late MIS 5. The recovery of several lithic assemblages in the Nefud exhibiting characteristics similar to MIS 5 Levantine sites lends support to these hypotheses. Palaeoclimate models (cf. Jennings et al., 2015) indicate no other arid barriers in central Arabia during the peak of MIS 5 (Figures 2 and 9), suggesting that groups could have moved deeper into Arabia, potentially providing a northern population source for MIS 5 sites in southern Arabia (Armitage et al., 2011; Rose et al., 2011; Groucutt et al., 2015c), or admixture with these groups if a southern route was their origin. Environmental, archaeological, and palaeohydrological data therefore collectively indicate that Levantine hominins, including *H. sapiens*, could have reached Arabia during the late Middle-Late Pleistocene via continental routes. This runs *contra* to hypotheses of early *Homo sapiens* outside of Africa being spatially isolated to the Levant, highlighting that in any such models clear mechanisms for this isolation should be proposed, given no apparent contemporary ecological or hydrological impediment to wider regional dispersals. However, given the absence of hominin fossils from Arabia, irrefutable confirmation of dispersals of *Homo sapiens* into this region from the Levant remains dependent upon future research. The rapidly increasing corpus of Pleistocene discoveries during recent years highlights that continued research focus upon northern Saudi Arabia will yield high returns in resolving this question.

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